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TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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IN AN ENGINE HAVING A HEMISPHERICAL

COMBUSTION CHAMBER

By A. M. Rothrock and Arnold E. Biermann
Langley Memorial Aeronautical Laboratory

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SUMMARY

Data are presented to show the effects of inlet-air
pressure, inlet-air temperature, and compression ratio on
the maximum permissible performance obtained with a cylin-
der having a hemispherical-dome combustion chamber. The
five aircraft-engine fuels used have octane numbers vary-
ing from 90 to 100 plus 2 ml of tetraethyl lead per gallon.
The data were obtained on a $5\frac{1}{4}$-inch by $4\frac{3}{4}$-inch liquid-
cooled engine operating at 2,500 rpm. The compression
ratio was varied from 6.0 to 8.9. The inlet-air tempera-
ture was varied from 110° to 310° F. For each set of con-
ditions, the inlet-air pressure was increased until audi-
ble knock occurred and then reduced 2 inches of mercury
before data were recorded. The results for each fuel can
be correlated by plotting the calculated end-gas density
factor against the calculated end-gas temperature. Meas-
urements of spark-plug electrode temperatures showed that,
with two spark plugs, cutting off the switch to one spark
plug lowered the electrode temperature of that plug from
a value of 1,365° F to a value of 957° F. The results in-
dicate that the surface temperatures of combustion-chamber
areas which become new sources of ignition markedly in-
crease after ignition commences.

INTRODUCTION

The N.A.C.A. has been conducting an investigation on
the knocking characteristics of high-octane fuels. Re-
sults obtained from an engine with a four-valve flat-disk
combustion chamber, from an engine with a four-valve pent-
roof combustion chamber, and from a C.F.R. engine have been
reported in references 1, 2, and 3, respectively.

Previous analyses of the problem of engine knock have shown that the most important independent variables in any one engine are the ones that control the end-gas density and temperature and the mixture ratio. The results from the previous tests showed that a certain amount of correlation exists between the knocking-characteristic curves obtained for several fuels used in different engines but that certain differences are caused by the variation in engine design.

The present report gives the data thus far obtained with a cylinder having a hemispherical-dome combustion chamber of aluminum alloy. Other cylinders tested at this laboratory for knocking characteristics have had cast-iron combustion chambers. The knocking characteristics were determined for five fuels over a range of compression ratios and inlet-air densities.

In the tests conducted at the N.A.C.A. laboratory with high antiknock fuels at high output, afterfiring from hot spark plugs has presented a serious problem except when the plugs have been water-cooled. Some information has been included in this report showing the effect of water cooling on the temperature of the spark-plug center electrode and also the difference in electrode temperatures of firing and nonfiring spark plugs.

APPARATUS AND METHODS

The aircraft-engine cylinder used during these tests had an aluminum-alloy head and jacket, with the head screwed and shrunk onto a steel barrel. This cylinder has a $5\frac{1}{4}$-inch bore and a $4\frac{3}{4}$-inch stroke, giving a displacement of 102.8 cubic inches. The combustion chamber is of the hemispherical type having two poppet valves operated through rockers by an overhead camshaft. The inlet-valve stem was sodium-cooled, and both the stem and the head of the exhaust valve were sodium-cooled. The two spark plugs in this cylinder are diametrically opposite and at an angle of approximately 45° with respect to a line between the valves. The compression ratio was changed by varying the spacer thickness under the cylinder flange.

Except where otherwise noted, the following quantities were held constant during these tests:

Valve timing - Inlet opens   30° B.T.C.

      Inlet closes   65° A.B.C.

      Exhaust opens   66° B.B.C.

      Exhaust closes   32° A.T.C.

Spark advance (retarded for
 1-percent drop in power) -   29°.

Engine speed - - - - - - - -   2,500 rpm.

Engine cooling - - - - - - -   ethylene glycol, outlet
           temperature, 250° F.

Fuel-air ratio (for maximum
 knock) - - - - - - - - - -   approximately 0.076.

Spark plugs - - - - - - - - -   BG 344-S.

  The fuel-air ratio was calculated from measurements of the weight of fuel and of the volume of air entering the engine. Thermocouples were used to measure the exhaust temperature, the wall temperature just above the piston travel on the inlet side, the flange temperature on the inlet side, the tip temperature of one spark-plug center electrode, and the mixture temperature. The mixture thermocouple was shielded. The calculated thermal conductivity of the spark-plug center electrode was impaired approximately 10 percent by installing the thermocouple in the electrode tip. For the tests in which the spark-plug electrode temperature was measured, the spark plug was located at the front of the engine near the exhaust valve. The outer shells of the spark plugs were water-cooled during all of the tests except the ones made to determine electrode temperatures. Peak cylinder pressures were obtained with the N.A.C.A. balanced-disk indicator. The higher values of the peak pressures correspond to the last intermittent flashes of the neon tube used with the maximum-pressure indicator; the lower values correspond to an almost steady flash of the neon tube.

  The inlet air was electrically heated. Because of the excessive time lag of electric heaters, it has been found difficult to change the inlet-air temperature rapidly and to hold it at the desired value. In the present set-up, these difficulties have been overcome by means of

a three-way valve; one intake port is connected to a source
of air at 500° F (thermostatically controlled), and the
other is arranged for inducting air at room temperature.
The air temperature can be rapidly changed by adjusting
this valve to admit different proportions of cold and hot
air.   The two air streams were mixed in a large tank before
entering the engine.

The procedure used in determining the knocking limita-
tion of a fuel was as follows: With a constant inlet-air
temperature and with the maximum-knock fuel mixture, the
inlet-air pressure was raised until audible knock occurred.
The inlet pressure was then arbitrarily reduced 2 inches of
mercury before data were taken. This procedure prevented
damage to the engine from running for prolonged periods un-
der knocking conditions and also avoided the necessity for
taking data while the engine was operating under the un-
stable conditions that accompany knock.

The fuels tested were made up from C.F.R. S-1 and
C.F.R. M-2 reference fuels with additions of tetraethyl
lead ($PbEt_4$); the following five fuels were tested:

Fuel	S-1 (percent)	M-2 (percent)	Tetraethyl lead, ml per gallon
1	90	10	0
2	95	5	0
3	100	0	0
4	100	0	1.0
5	100	0	2.0

In the table and the curves, the fuels are referred
to by the percentage of S-1 and the tetraethyl-lead con-
tent. Tests were conducted at compression ratios of 6.0,
7.5, and 8.9 and at five inlet-air temperatures covering
the range from 110° to 310° F.

The engine-performance data were computed by the meth-
od outlined in reference 1.

RESULTS AND DISCUSSION

Knocking Characteristics

The principal test results, giving the engine perform-
ance for inlet pressures of 2 inches of mercury below the
audible-knock inlet pressure, are presented in table I.
As shown by the data, some of the test conditions were re-
peated at another time with somewhat different results; a
considerable difference occurred in the specific fuel con-
sumptions and the cylinder temperatures. Although no ex-
planation has been found, differences in piston-ring con-
dition or the presence of afterfiring probably accounts
for some of these discrepancies.

In figure 1, the power developed with the several
fuels (for inlet-air pressure for audible knock less 2
inches of mercury) is presented for the three compression
ratios. Curves of the peak cylinder pressures obtained
for three inlet-air temperatures and two compression ratios
are shown in figure 2. The experimental values (table I)
have not been placed on the curves because the points are
scattered. The curves as drawn represent the general
trend of the data. The pressure values given are the
lower readings of the N.A.C.A. balanced-disk maximum-
pressure indicator.

It was pointed out in reference 1 that whether knock
takes place in an internal-combustion engine depends on
the density and the temperature in the end gas. Reference
2 shows that the end-gas density approaches a maximum value
expressed by

$$K\rho_3 = \frac{RP_1}{T_1}\left(1 + \frac{H}{c_V T_1 R^{\gamma-1}}\right)^{\frac{1}{\gamma}}$$

in which ρ_3 gas density in knocking zone immediately
                preceding knock.

P_1 inlet-air pressure.

T_1 inlet-air temperature.

γ adiabatic coefficient.

c_V specific heat of mixture at constant volume.

     R   compression ratio of engine.

     H   heat content per pound of mixture.

     K   a constant.

It has also been shown in reference 2 that the end-gas temperature T_3 approaches a maximum value expressed by

$$T_3 = T_1 R^{\gamma-1} \left(1 + \frac{H}{c_v T_1 R^{\gamma-1}}\right)^{\frac{\gamma-1}{\gamma}}$$

An analysis of the results presented in reference 2 showed that fairly good correlation of the data from a pent-roof and a flat-disk type of combustion chamber could be obtained by simplifying the density expression to RP_1/T_1 and by using the inlet-air temperature instead of the expression for T_3. An attempt to correlate the data of the present report in a similar manner is shown in figure 3. A fairly wide spread of the data is noticed for the different compression ratios, especially for the 90- and the 95-percent S-1 fuels. In general, the 100-percent S-1 and the S-1 plus tetraethyl lead could not be used at the lowest compression ratio because of the limitations of the apparatus as regards boost.

As shown by figure 4, a somewhat better correlation of the present data is obtained by substituting $T_1 R^{\gamma-1}$ for the inlet-air temperature. The spread of the points, however, does not justify the use of these factors.

A still further improvement in the correlation of the present data is obtained by using the more exact expressions for the density factor, $K\rho_3$, and the estimated end-gas temperature, T_3. These results are plotted in figure 5. Although some scatter of the points is apparent, this scatter is, in general, less than the discrepancy between the sets of data at the same compression ratios.

In reference 2 it was noted that the coordinate RP_1/T_1 could not be used for the C.F.R. engine, and the difference between the coordinates used to correlate the data for the C.F.R. engine and for the larger engines reported in reference 1 was attributed to the difference in

displacement of the engines. The present results, how-
ever, showed that, for an engine similar in size to those
discussed in reference 1, the best correlation was ob-
tained when the calculated values of $K\rho_3$ and T_3 were
used as the coordinates for the knock-rating curves of the
different fuels. The difference in the criteria giving
the best correlation of the knock data for the engines
discussed in reference 2 and for the present engine must
therefore be concluded to be a result not of engine size
but of the interrelation of several engine factors. As
long as there are differences in engine design or until
the end-gas temperature and density can be directly meas-
ured, these differences in correlating factors will prob-
ably continue and must be attributed to the engine rather
than to the fuel.

Spark-Plug Electrode Temperatures

Some temperature measurements of the tip of the cen-
tral electrode of one spark plug are presented in figure
6. The curves in this figure were obtained by progressive-
ly increasing the inlet pressure until knock occurred. In
one instance, cutting the front-plug ignition switch caused
a reduction in temperature from 1,365° to 957° F. The fact
that the nonfiring spark plug was probably in the end-gas
zone during knock raised its temperature very little above
the normal course of the curve. The heating effect of the
spark itself caused a negligible rise in electrode temper-
ature, as determined by opening and closing the ignition
switch while motoring the engine.

Water-cooling the nonfiring spark plug lowered the
electrode temperature from 970° to 870° F. A slightly
greater drop in the temperature of the firing spark plug
would probably result from water cooling.

The information presented in figure 6 also shows what
may result when overheated combustion-chamber surfaces be-
come auxiliary sources of ignition. Once ignition starts
from an overheated surface, the temperature of the surface
may rise somewhat, as shown in figure 6, depending upon
the location of the surface with respect to a spark plug.
The reasons for this rise in the temperature of the region
where ignition starts as given by Lewis and von Elbe in
reference 4 may be condensed as follows: At the source of
ignition, the burning gas expands at a practically constant
pressure, which is the compression pressure. It is subse-

quently compressed to nearly its original volume by the
combustion of the rest of the gas in the chamber. The work
of compression exceeds the work of expansion because the
compression of the gas at the source of ignition takes
place at a steadily increasing pressure; whereas, the ex-
pansion took place at the lower initial pressure. As a
result, the gas remote from the source of ignition loses
some of its energy but the gas at the source of ignition
gains energy in excess of the chemical energy released
within it. The result is a temperature gradient, rising
toward the source of ignition, the temperature difference
of which amounts to several hundred degrees.

The data in figure 6 indicate why, under certain cir-
cumstances, preignition can lead to very rapid engine
failure. Assume that, because of unequal cooling through-
out the cylinder, the hottest spot in the combustion-
chamber surface is in the end-gas zone. Once preignition
starts in this zone, the zone is no longer the end-gas
zone but becomes the first part of the charge to burn.
This change of the gas surrounding the hot spot from the
end-gas zone to the first part of the charge to burn can
cause an increase in the surface temperature at the hot
spot of as much as 400° F, as shown by figure 6. This in-
crease in the temperature of the hot spot will advance the
timing of the preignition, which will further increase the
hot-spot temperature. This unstable condition will lead
to earlier ignition of the charge on each successive cycle
and to eventual failure of the engine. The rapidity of
the engine failure, once the preignition has started, de-
pends on the rapidity with which the foregoing actions
take place.

CONCLUSIONS

The results of the present tests of five fuels in a
cylinder having a hemispherical-dome combustion chamber
showed that:

1. The data on knock could be correlated by plotting
the calculated end-gas density factor, $K\rho_3$, against the
calculated end-gas temperature, T_3.

2. The particular factors used to correlate knocking
test data depend upon the engine design; until the end-gas
temperature and density can be directly determined, there
will be differences in the correlating factors.

3.   Cutting off the ignition from one of two spark plugs lowered the electrode temperature of that plug from 1,365° to 957° F.

4.   Surface temperatures of combustion-chamber areas that become new sources of ignition may increase markedly after ignition commences.

Langley Memorial Aeronautical Laboratory,
    National Advisory Committee for Aeronautics,
        Langley Field, Va., May 2, 1940.

REFERENCES

1.   Rothrock, A. M., and Biermann, Arnold E.: Engine Performance and Knock Rating of Fuels for High-Output Aircraft Engines. T.N. No. 647, N.A.C.A., 1938.

2.   Rothrock, A. M., and Biermann, Arnold E.: The Knocking Characteristics of Fuels in Relation to Maximum Permissible Performance of Aircraft Engines. T.R. No. 655, N.A.C.A., 1939.

3.   Lee, Dana W.: The Effects of Engine Speed and Mixture Temperature on the Knocking Characteristics of Several Fuels. T.N. No. 767, N.A.C.A., 1940.

4.   Lewis, Bernard, and von Elbe, Guenther: Combustion, Flames and Explosions of Gases. Univ. Press (Cambridge), 1938, p. 167.

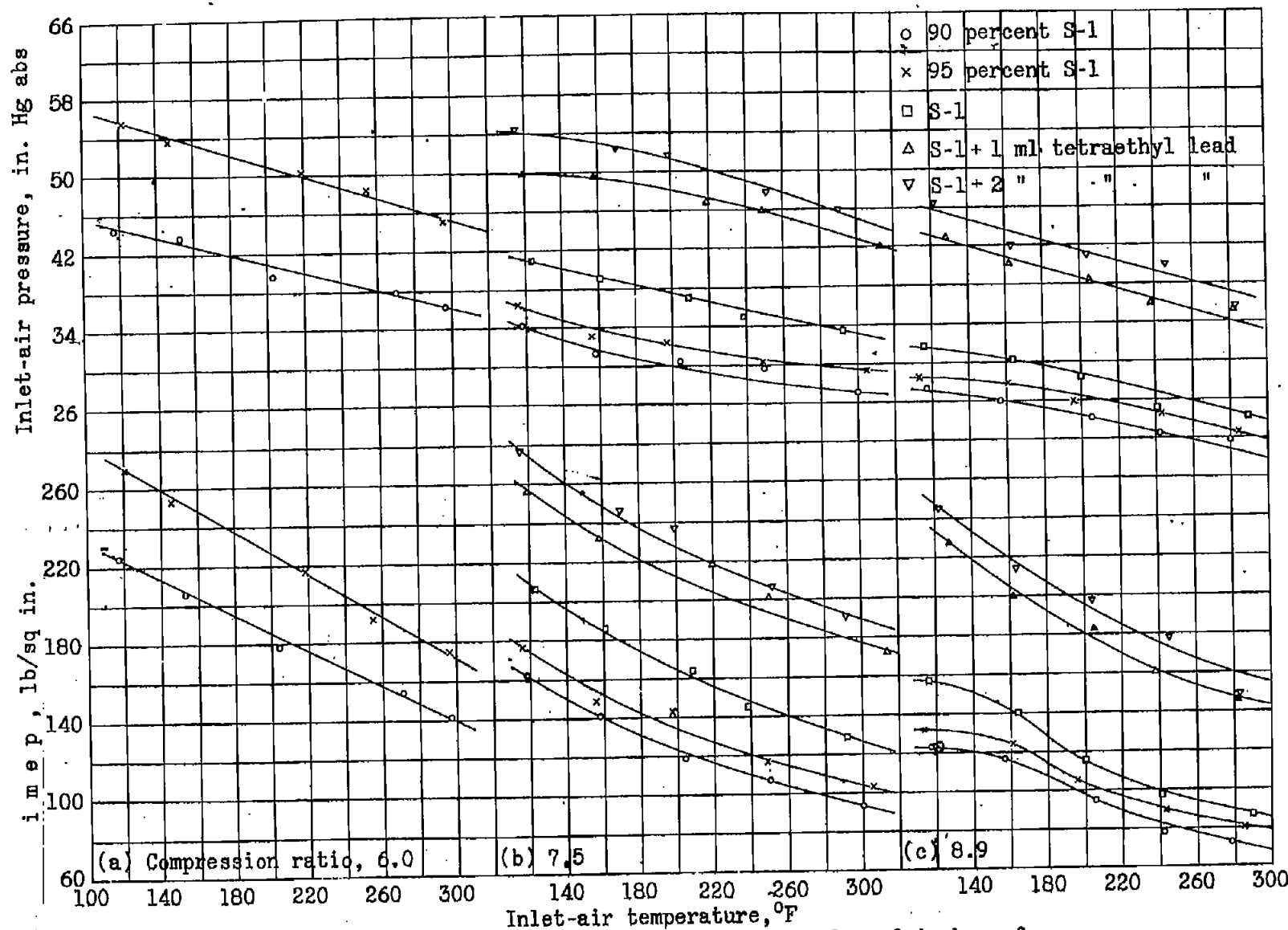| Fuel	Compression ratio	Inlet-air temperature (°F)	Mixture temperature (°F)	Inlet pressure (in. Hg absolute)	imep (lb/sq in.)	Indicated fuel consumption (lb/ihp/hr)	Peak pressure (low)	Peak pressure (high)	Exhaust temperature (°F)	Flange temperature (°F)	Wall temperature (°F)
90 percent S-1	6.0	[a]117	98.0	44.5	225	0.433	825	950	1,331	248	—
		[a]153	117.9	43.7	206	.453	800	1,000	1,311	202	—
		[a]204	164.8	39.7	178	.451	780	900	1,279	222	—
		[a]271	211.6	37.8	155	.462	630	800	1,270	200	—
		[a]297	244.2	36.4	141	.463	580	750	1,264	219	—
		125	95.5	46.4	226	.535	-	-	-	350	385
		173	136.3	44.5	203	.583	-	-	-	309	376
		212	171.5	42.3	180	.588	-	-	-	366	373
		257	210.0	41.4	169	.600	-	-	-	355	383
		302	246.8	38.2	149	.590	-	-	-	336	364
	7.5	118	110.1	34.2	162	.479	-	-	-	233	330
		158	132.8	31.4	141	.485	-	-	-	229	324
		204	164.7	30.4	119	.481	-	-	-	207	317
		250	198.1	29.5	107	.542	-	-	-	221	322
		300	207.8	28.8	94	.481	-	-	-	196	320
	8.9	117	96.7	27.3	123	.430	535	600	1,364	293	316
		157	126.6	26.0	117	.410	525	600	1,321	300	313
		206	161.8	24.2	95	.408	460	590	1,351	300	308
		242	176.0	22.6	78	.440	425	525	1,302	268	304
		279	192.8	21.8	73	.470	425	525	1,302	263	297
		127	98.2	24.9	118	.399	590	775	1,403	285	256
		170	139.0	23.9	105	.434	550	730	1,384	268	238
		212	169.0	22.7	94	.424	430	580	1,372	280	240
		258	208.5	21.1	79	.449	360	540	1,378	277	237
95 percent S-1	6.0	[a]121	91.3	55.6	270	.454	1,050	1,200	1,345	206	267
		[a]146	119.9	53.7	253	.460	1,050	1,250	1,314	229	258
		[a]219	176.0	50.3	217	.475	900	1,100	1,313	204	246
		[a]255	214.9	48.3	192	.492	780	950	1,307	213	240
		[a]296	251.2	45.2	176	.480	760	900	1,287	264	253
		135	95.1	49.2	239	.484	-	-	-	364	378
		173	135.0	47.9	226	.522	-	-	-	319	375
		215	175.0	46.4	202	.514	-	-	-	342	384
		256	207.0	45.2	187	.509	-	-	-	353	380
		297	241.0	39.3	159	.526	-	-	-	344	382
	7.5	118	110.1	36.4	177	.455	-	-	-	234	336
		156	128.3	33.1	149	.450	-	-	752	231	325
		197	162.2	32.3	143	.470	-	-	752	250	329
		249	196.8	30.2	117	.480	-	-	1,168	206	321
		305	216.6	29.3	103	.530	-	-	1,144	183	318
	8.9	113	92.0	28.6	132	.407	600	800	1,380	310	327
		161	129.3	27.8	124	.407	575	725	1,367	301	314
		196	148.5	25.8	105	.420	575	750	1,343	270	314
		243	173.2	24.6	90	.420	525	600	1,356	273	311
		285	198.2	23.3	81	.400	400	600	1,346	281	308
		126	101.5	27.1	133	.481	630	900	1,321	275	256
		171	134.0	27.5	134	.437	-	-	1,349	283	238
		215	171.9	25.3	107	.409	-	-	1,377	266	210
		255	197.4	23.7	94	.482	-	-	1,383	269	214
		300	225.0	21.1	73	.502	-	-	1,365	208	218
S-1	7.5	123	101.4	41.0	206	.453	-	-	1,375	231	356
		161	129.9	39.0	186	.441	-	-	1,297	229	348
		209	167.9	37.1	164	.446	-	-	1,240	245	345
		239	199.5	34.9	145	.453	-	-	1,223	228	333
		292	239.1	33.5	129	.457	-	-	1,217	190	327
	8.9	118	95.0	31.7	157	.388	800	900	1,389	314	327
		164	133.3	30.2	140	.435	775	925	1,384	307	317
		200	159.9	28.4	115	.461	600	800	1,379	292	312
		241	175.7	26.1	96	.458	475	600	1,364	277	309
		290	196.5	24.2	87	.443	425	500	1,355	275	306
		128	98.3	31.6	167	.473	-	-	1,326	301	244
		171	137.8	28.8	141	.466	-	-	1,364	290	244
		216	175.2	27.3	120	.472	-	-	1,359	276	215
		259	203.2	25.1	99	.508	-	-	1,358	274	209
		297	226.0	23.1	86	.494	-	-	1,383	269	222
S-1+1 ml PbEt4	6.0	[a]292	234.1	57.5	243	.481	860	1,100	1,348	247	-
	7.5	[a]119	118.8	49.9	257	.456	-	-	-	-	-
		[a]158	113.9	49.5	233	.441	-	-	1,209	258	385
		[a]230	163.6	46.8	219	.442	-	-	1,180	160	378
		[a]250	195.8	45.9	201	.463	1,150	1,250	1,178	168	376
		[a]313	248.2	42.1	173	.446	900	1,000	1,187	173	365
	8.9	138	100.0	43.0	227	.413	-	1,250	-	288	342
		162	137.6	40.2	200	.409	-	-	-	232	341
		205	173.9	38.5	183	.406	-	-	-	273	339
		238	195.8	36.0	160	.410	850	1,050	-	312	332
		282	229.4	34.6	146	.414	750	1,050	-	303	333
S-1+2 ml PbEt4	7.5	[a]115	82.6	54.3	277	.438	-	-	1,247	253	385
		[a]170	126.0	52.2	246	.445	-	-	1,195	265	397
		[a]199	156.9	51.5	237	.446	-	-	1,209	233	379
		[a]252	206.2	47.8	206	.433	1,200	1,325	1,198	182	370
		[a]291	228.4	46.0	191	.437	1,100	1,300	1,189	175	373
	8.9	122	93.0	46.6	245	.403	1,100	1,300	-	340	348
		163	136.0	42.1	214	.475	-	-	-	291	341
		204	173.2	41.0	198	.466	-	-	-	246	339
		246	200.8	40.1	178	.468	1,000	1,150	-	315	335
		283	229.7	35.7	149	.476	750	1,075	-	312	335

[a] Accompanied by afterfiring.

Fig. 1

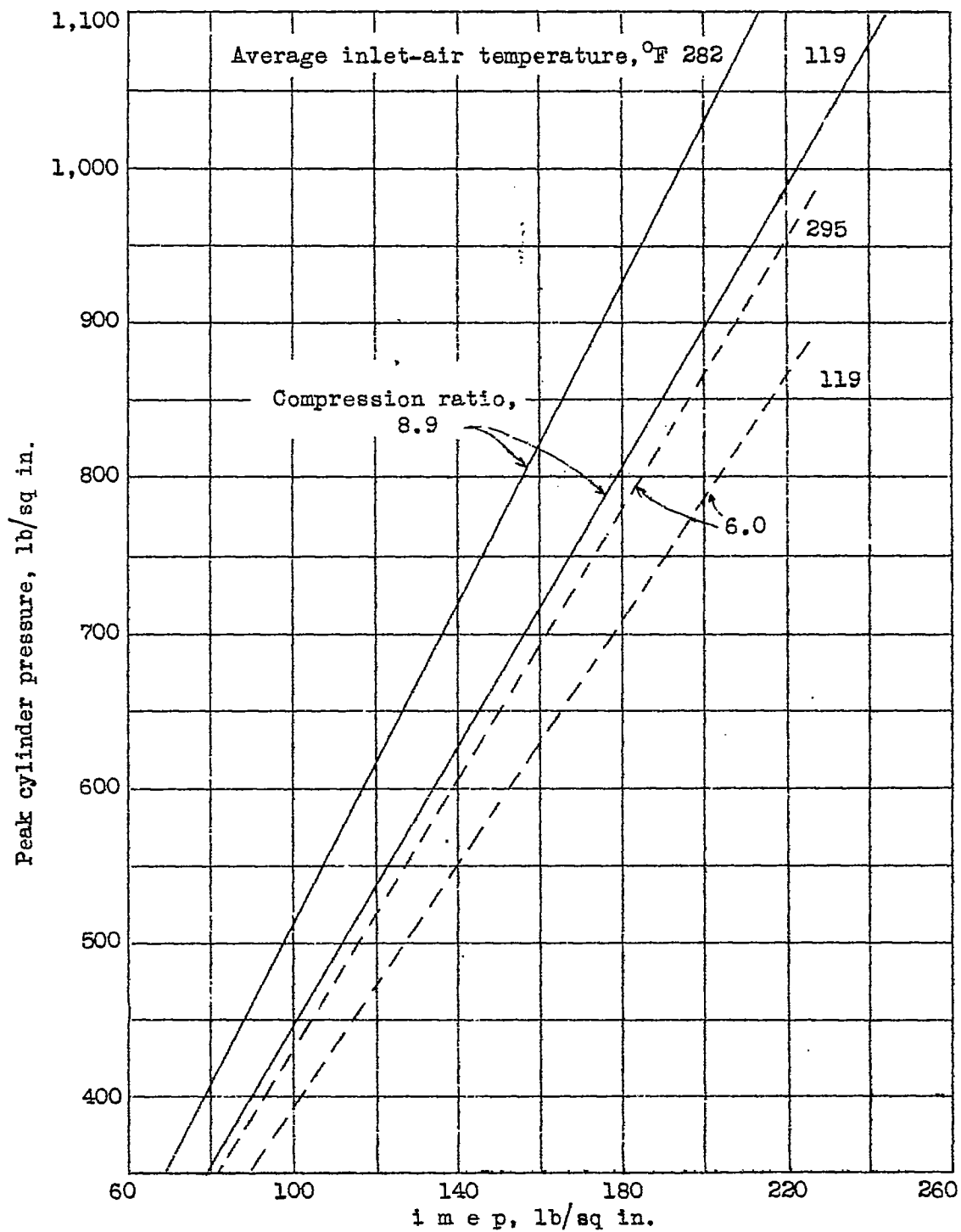Figure 1 a to c.- Engine performance for audible-knock pressure less 2 inches of mercury.

Figure 2.- Variation of maximum cylinder pressure with inlet-air
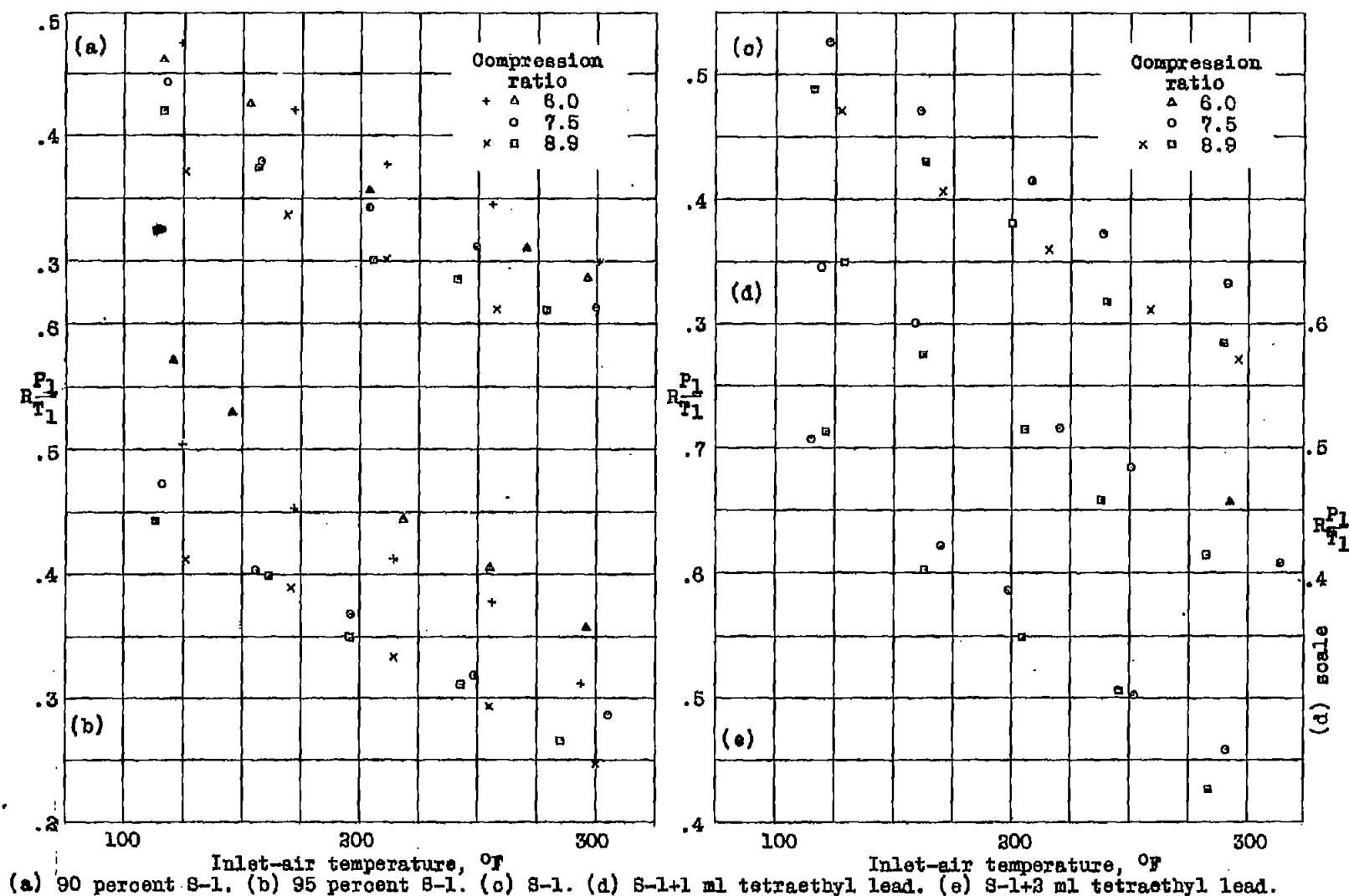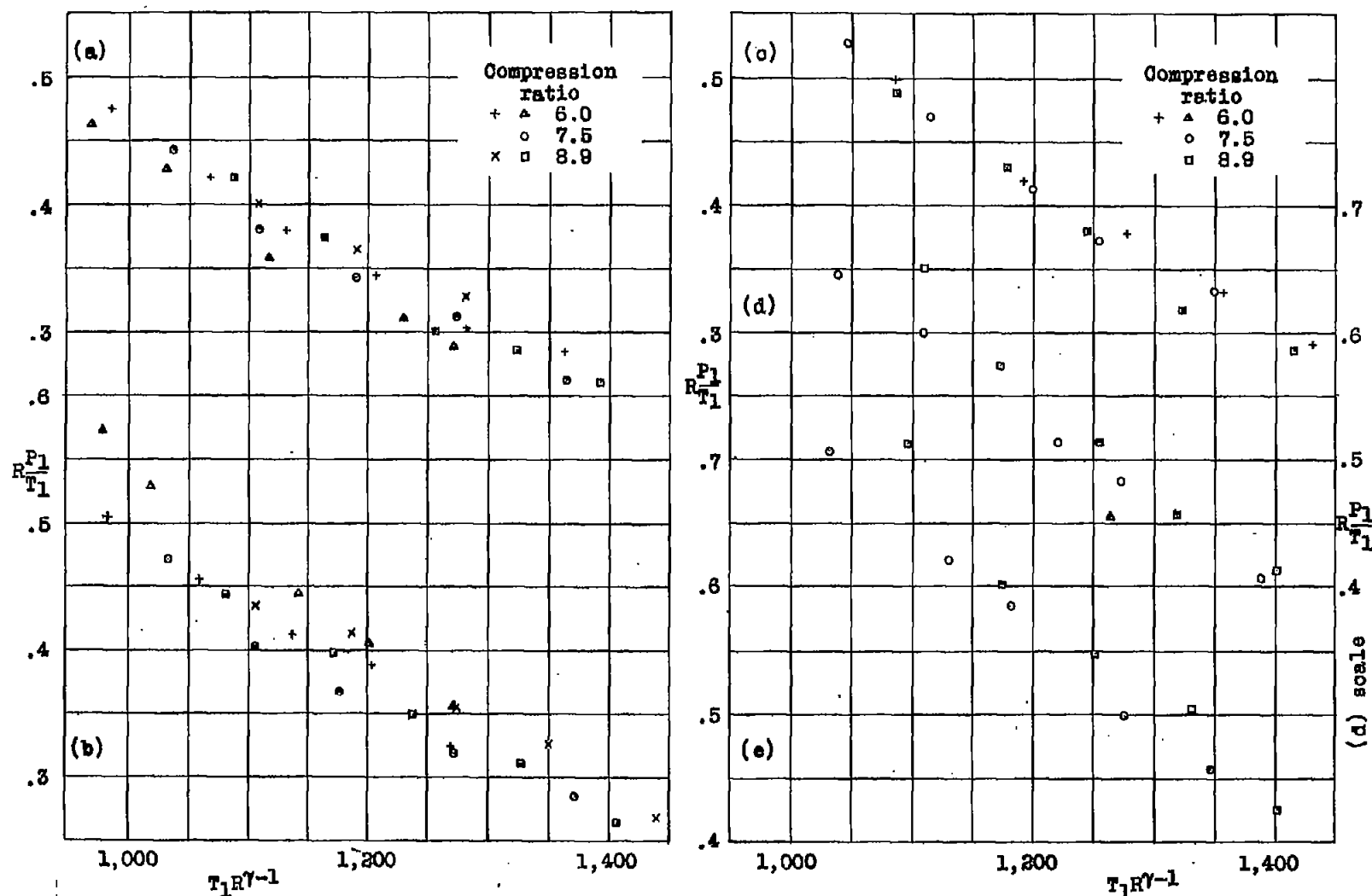temperature and compression ratio.

(a) 90 percent S-1. (b) 95 percent S-1. (c) S-1. (d) S-1+1 ml tetraethyl lead. (e) S-1+3 ml tetraethyl lead.

Figure 3 a to e.- Effect of inlet-air temperature on the maximum permissible density factor, $R\frac{P_1}{T_1}$

Fig. 3

(a)

Compression
ratio
+ △ 6.0
○ 7.5
× □ 8.9

(c)

Compression
ratio
+ △ 6.0
○ 7.5
□ 8.9

$R\dfrac{P_1}{T_1}$

.6
.5
.4
.3

.7
.8
.5
.4
.3

(b)

(d)

(e)

$R\dfrac{P_1}{T_1}$

$R\dfrac{P_1}{T_1}$

.5
.7
.6
.5
.4

.4
.7
.6
.5
.4

(d) scale

1,000   1,200   1,400

$T_1 R^{\gamma-1}$

1,000   1,200   1,400

$T_1 R^{\gamma-1}$

(a) 90 percent S-1. (b) 95 percent S-1. (c) S-1. (d) S-1+1 ml tetraethyl lead. (e) S-1+2 ml tetraethyl lead.

Figure 4 a to e.- Relationship between the temperature factor $T_1 R^{\gamma-1}$ and the maximum permissible density factor, $R\dfrac{P_1}{T_1}$.

Fig. 4

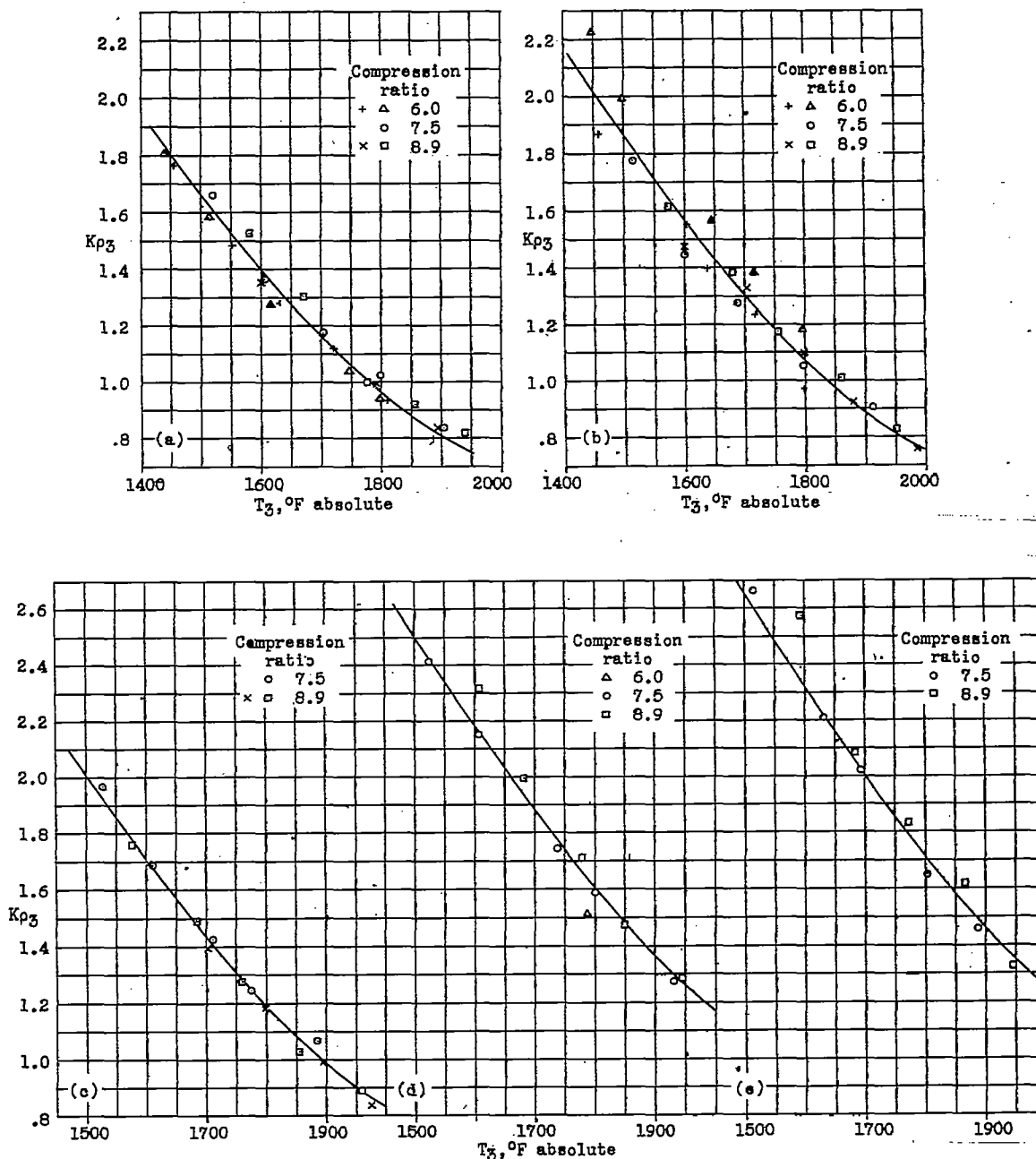(a) 90 percent S-1. (b) 95 percent S-1. (c) S-1. (d) S-1+1 ml tetraethyl lead. (e) S-1+2 ml tetraethyl lead.

Figure 5 a to e.- Effect of estimated temperature T_3 of end-gas on the maximum permissible end-gas density factor, $K\rho_3$.
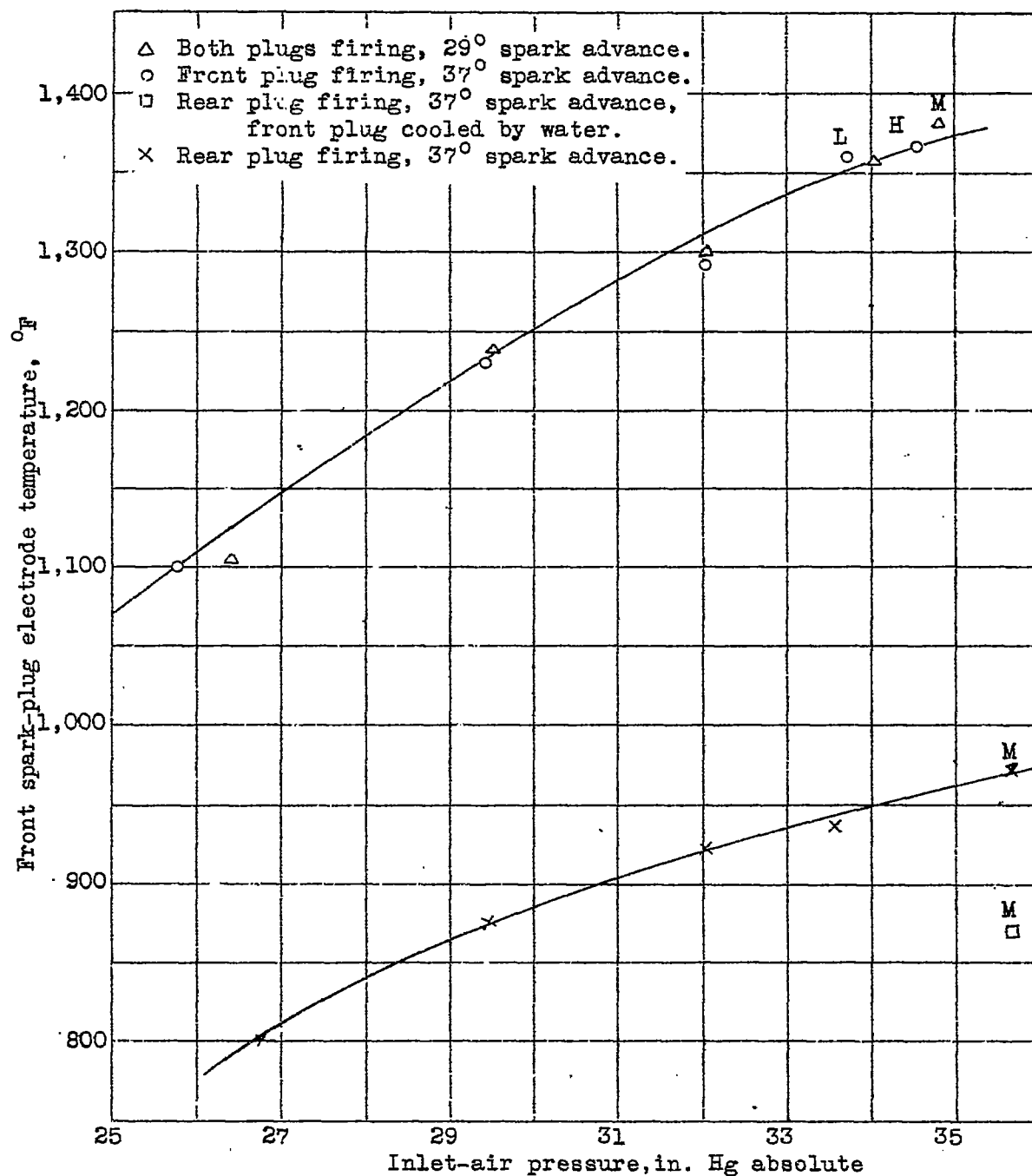
Figure 6.- Front spark-plug electrode temperatures with the plug firing
and not firing and with water flowing over the plug. Com-
pression ratio,7.5; engine speed,2,000 rpm; maximum-knock mixture; inlet-
air temperature,120°F; ethylene glycol temperature,240°F; S-1 fuel; spark
retarded for 99 percent maximum power. L, light pinking knock; M, medium
loud knock; H, hard knock.